Macroalgae Blooms and Nearshore Habitat and Resources of the Strait of Juan de Fuca

J. Anne Shaffer
Washington Department of Fish and Wildlife

Abstract
Macroalgae blooms, promoted by nutrient loading, have been documented in other areas of the world to result in dramatic changes to nearshore ecosystems. Macroalgae blooms in inland marine waters of Washington are theorized to be increasing, and documented to occur in areas critical for a number of federally listed salmonid species, including the nearshore areas of the Strait of Juan de Fuca. This study synthesizes information on ulvoid blooms in the Strait, and includes a number of important findings, including a significant correlation between mat size and proximity to creeks and culverts, shoreline alterations, and fecal coliform levels, and significant inverse correlation with fetch. Dungeness Bay experienced a 261% increase in ulvoid mat coverage over the last 7 years, and a 63% decrease in eelgrass in one bed over the last 8 years. Significant differences in nearshore habitat physical and biological features, including substrate profiles and shellfish resources, were observed in areas with dense ulvoid coverage.

Introduction
Macroalgae blooms, locally known as ulvoid blooms, are an opportunistic green macroalgae that form dense mats which reduce light and oxygen, creating an anoxic environment (Hull 1987; Hernandez and others 1997). These blooms, which are controlled largely by nutrient levels, may have a negative impact on nearshore invertebrate and fish communities, as well as other vegetated habitats such as eelgrass beds (Blankenship 1993; Carpenter and others 1998; Hagerman and others 1996; Inkpen and Embry 1998; Frankenstein 2000; Isaksson and others 1994; Macfarlane 1988; Shaffer and Burge 1999; Short and others 1995; Sogard & Able 1991; Vitousek and others 1997; Wilson 1993; Wright 1989). Areas where blooms occur are also often prime shellfish and finfish habitat.

Washington State is a world leader in recreational and commercial shellfish resource use and home to at least three federally listed species of salmon, including Puget Sound chinook (*Oncorhynchus tshawytscha*) and Hood Canal Summer chum (*Oncorhynchus keta*) salmon, and Bull trout (*Salvelinus malma*). Sand lance, (*Ammodytes hexapterus*), surf smelt (*Hypomesus pretiosus*) and herring (*Clupea pallas)*, forage fish for salmonid species, listed as species of special concern and regulated by state law (RCW 77.55.100-55.200), depend on nearshore areas including gravel/sand beaches and eelgrass beds for both migration and spawning. Thom and others 1988 first documented the important role nonpoint nutrient sources play in the creation of ulvoid mats in Puget Sound. Observations by various managers over the last 15 years indicate that ulvoid mats may be increasing, and therefore a growing concern for managers of Washington's nearshore habitat (Frankenstein 2000). Unfortunately little information exists on ulvoid mat presence, trends, and resource impact in Washington waters.

The Strait of Juan de Fuca offers some of the most diverse nearshore habitats in the state of Washington (Shaffer 2000). Intertidal shellfishing in the Strait of Juan de Fuca is an important recreational and commercial industry. Nearshore areas of the Strait are critical migration corridors for all salmonid species. Eelgrass beds of the eastern Strait support spawning for important, and declining, herring stocks (Washington State Department of Fish and Wildlife unpublished data), and intertidal beaches of the Strait provide spawning habitat for surf smelt and sand lance (Penttila 1999). Various attributes of ulvoid mats along the central and western Strait have been documented and studied over the last five years, and a number of linkages between physical attributes of ulvoid mats, resource, and habitat are beginning to emerge, but results have not been synthesized.

This paper provides a synthesis of knowledge about macroalgae blooms in the Strait of Juan de Fuca, including current distribution, possible causative factors, long term trends in ulvoid mat coverage, and observed impacts to shellfish and forage fish habitat and resource. The synthesis provides direction for work in other areas of Washington nearshore, and includes recommendations to marine habitat managers and researchers on the role of ulvoid mats to nearshore environment

Methods and Materials

Results from a number of completed studies were compiled in this synthesis. They include:

Johannessen and Chase (2001). Southern Dungeness Bay shoreline change and management
Penttila (1999) Forage fish spawning maps for Clallam County
Shaffer and Burge (1999) Ulvoid mats and shellfish resources of the Strait of Juan de Fuca: a pilot study.
Shaffer (2000) Nearshore mapping of the central and western Strait of Juan de Fuca
Washington Department of Natural Resources (DNR; ongoing) Mapping of nearshore habitats of Washington state
Washington Department of Health (DoH; ongoing) Water quality monitoring of Washington state.

Field methods for each of the completed studies are described within each report, and will not be repeated here. Full citations for each of these are provided in the bibliography.

Thom and others (1988) documented clear linkages between nutrient levels and ulvoid blooms in a number of Puget Sound embayments. Unfortunately long-term nutrient data do not exist for most of the Strait of Juan de Fuca. Fecal coliform monitoring has been occurring along the Strait of Juan de Fuca since 1989. Fecal coliforms themselves are not nutrients and do not contribute to ulvoid blooms. Sources for fecal coliform however are also sources of nutrients. In this study then, trends in water quality and ulvoid mat coverage were assessed using fecal coliform concentrations as an indicator of nutrients levels.

The synthesis also includes information from a study defining the long term and seasonal variation of ulvoid mats in Dungeness Bay (Shaffer in progress). Methods for this work are described below.

Dungeness Bay was studied in for (1) long-term changes in areal coverage of ulvoid mats; and (2) the relationship between these mats and shellfish resources and forage fish spawning habitat. Long-term changes were determined by comparing 1994 and 2000/2001 aerial photography of target areas. Year 2000 photography was taken once per season at a minimum of a 0.0 tide during daylight hours. All photos were taken at 1000 feet from either a helicopter or fixed wing airplane. Color infrared and straight color film was used. July 2000 air photos were projected onto a screen and ulvoid coverage within 500 feet of forage fish spawning area mapped onto a DNR orthophoto (1:12,000 scale). Historic coverage was obtained by downloading Washington State Department of Ecology 1994 shoreline coverage, and mapping ulvoid mats along target areas onto georeferenced DNR orthophotos. Aerial coverage July 1994 and 2000 were then digitized (in acres and square kilometers) and compared.

Results

I. Prevalence of Ulvoid mats along the central and western Strait and physical parameters of ulvoid mats in Strait of Juan de Fuca (Shaffer 2000).

A total of 13 beaches, totaling 19.85 miles were sampled for ulvoid mats (Table 1).

Table 1. Ulvoid mapping summary, Strait of Juan de Fuca, July 2000.

Beach	***Miles sampled***	***Mat Percent cover***	***Mat volume ($L/0.25m^2$)***	***Mat depth, cm***
Dungeness Bay				
Three Crabs	0.75	100	12.00	41
Cline Spit	1.00	80	1.00	0.85
Outer Dungeness Spit	3.00	48	0.500	0.83
Inner Dungeness Spit	1.00	2	0.13	0.44
Jamestown	2.00	98.	1.60	1.42
Total/Average	**7.75**	**66**	**3.00**	**8.82**
Stdev	**----**	**41**	**4.9**	**17.75**
Morse Creek	2.00	48	0.65	0.75
Freshwater Bay	2.00	33	0.57	0.29
Butler Cove	0.10	0	0	0
E. Twin Rivers	2.00	17	0.13	0.21
E.Elwha/Dry Creek	2.00	0	0	0
E.Lyre/Whiskey	2.00	0	0	0
Pysht	1.00	0	0	0
DeepCreek/W. Twin River	1.00	0	0	0
Total/Average	**12.10**	**12**	**0.17**	**0.16**
Stdev	**------**	**19**	**0.28**	**0.27**

Ulvoid coverage varied by beach, and was significantly correlated to proximity to creeks and small drainages (Spearmans rank correlation R^2=0.6619; $R^2_{crit\ 12(01,\ 05)}$=0.587), as well as to fecal coliform(fc) levels (R^2=0.9668; $R_{crit\ 3(\ 01,\ 0.05)}$=0.805 Ulvoid coverage was also inversely correlated to fetch (R^2=-0.748; $R^2_{crit\ 12(01,\ 05)}$=0.587). Dungeness Bay beaches had the highest coverage overall, with an average percent coverage of 66%, an average volume of 3 liters per quarter meter square, and an average depth of 8.82 cm.

Ulvoid volumes on beaches outside of Dungeness Bay were much lower (Table 1), and limited to the beaches adjacent to Ennis Creek (located at the western end of the Morse Creek beach), a small creek at the western end of Freshwater Bay, and East Twin Rivers with percent coverages of 48, 34, and 18% respectively.

II. Long term monitoring of ulvoid mats in Dungeness Bay (Shaffer, in progress):

A. **Areal mapping.**: Coverage of ulvoid mats along the shorelines of Dungeness Bay has increased an average of 261% from 1994 to 2000 (Table 2). This increase coincides with significant increase in fecal coliform (fc) levels within the Bay from 1989-2000 (F=2.28; $F_{crit\ (11,2,\ 0.05)}$ =1.809; p=0.0103)

Table 2. Long term trends in ulvoid coverage, Dungeness Bay.

Site	Acres		Square feet		Change	
	1994	2000	1994	2000	acres	%
GraysMarsh	1.72	5.6	74897	244310	9	226
Three Crabs	7.59	58.2	330560	2533618	8	666
Cline Spit	4.0	3.6	174405	155178	-0.44	-11
Golden sands	0	8.1	352215	0	8.1	810
Cooper Crk	10.53	4.21	183297	458533	-6.32	-60
Southern Spit	0.704	0.229	30,653	9,956	-0.475	-67
			Average			261
			Stdev			388

B. **Eelgrass**. (Mumford and others Unpublished data and Shaffer and Burge 1999). One eelgrass bed within Dungeness Bay was field mapped by both DNR in1990 and Shaffer and Burge 1998. Comparing eelgrass percent coverage within this bed documented in the two studies revealed eelgrass relative coverage in this one study area declined from 63% to 0%. Ulva has replaced eelgrass in vegetation cover (Table 3).

Table 3. Macrovegetation coverage in outer Three Crabs area of Dungeness Bay 1990 and 1998

Date	Number of samples	Total percent cover	Relative percent cover, eelgrass	Relative percent cover ulvoid
1990	28	106	63	37
1998	14	90	0	100
Change		***-16%***	***-63%***	***+63%***

III. Relationship between ulvoid mats and biological resources

A. Shellfish (Shaffer and Burge 1999). When shellfish resources of an ulvoid (Dungeness Bay) and non-ulvoid (Bywater Bay) beaches of the Strait of Juan de Fuca were compared, a number of differences were found, including: significantly higher densities of live Manila (*Venerupis philippinarum)*, butter (*Saxidomous nutalli)*, soft shell (*Mya arenaria*), and macoma (*Macoma* spp.) clams, and cockles (*Clinocardium nuttallii)* on the non-ulvoid beach; significantly larger, and higher numbers of dead native and butter clams on the ulvoid beach (Figure 1).

Substrate composition of the two beaches showed a number of differences. The ulvoid beach offered more substrate types, and was dominated by finer substrate, with 13 % more mud than the non-ulvoid beach. The non-ulvoid beach had a larger proportion of sand, cobble, and gravel mixed substrates than the ulvoid beach. Beach profiles of the two embayments appeared to be reversed, with the larger proportion of fine material occurring at the shoreward edge of the beach on the ulvoid beach (Figure 2).

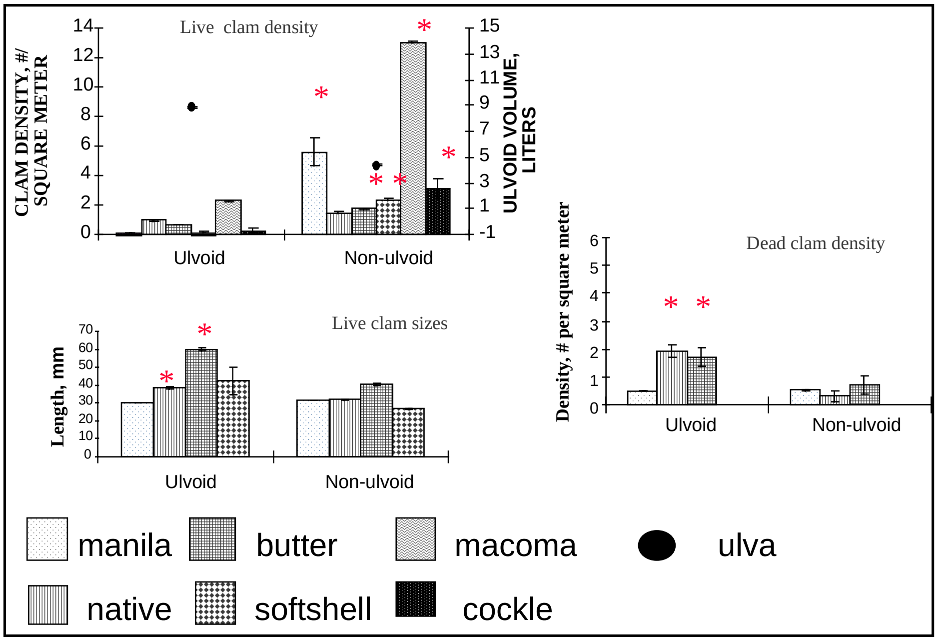

Figure 1 Live and dead clam density and sizes on ulvoid and non-ulvoid beaches *=significant ($p<0.05$).

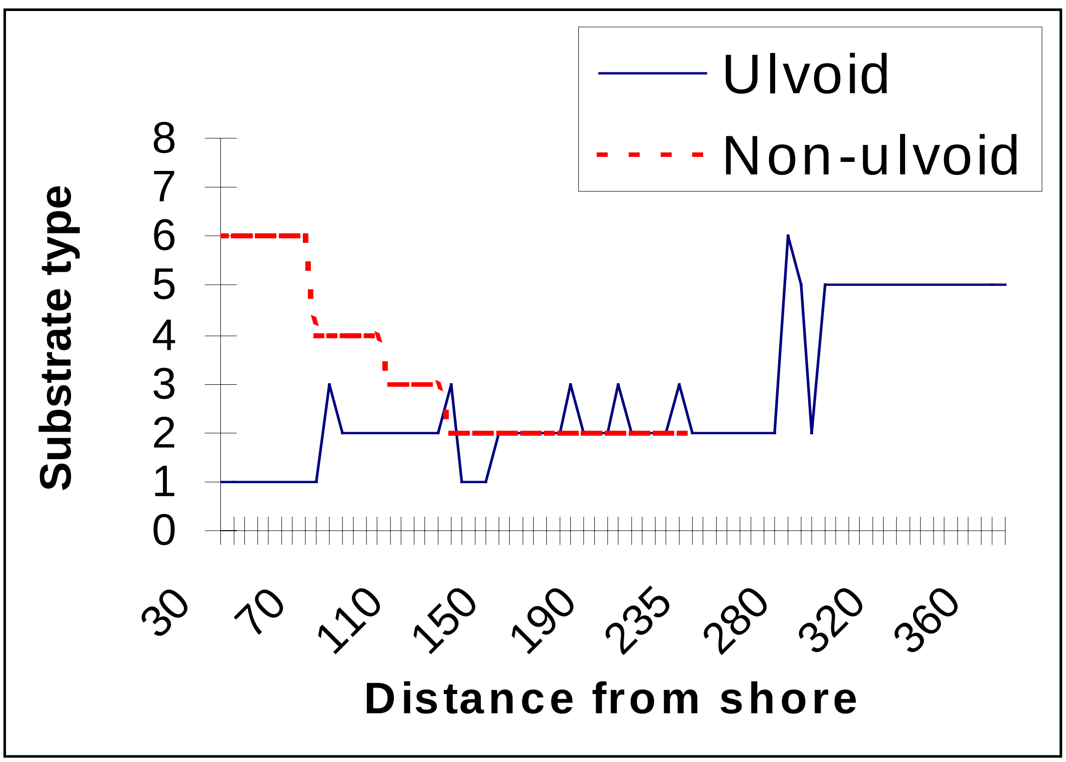

Figure 2 Beach profiles of ulvoid and non-ulvoid beaches
(1=mud;2=sand/mud;3=sand;4=sand/gravel;5=gravel;6=cobble;7=boulder; 8=bedrock)

B. Forage Fish (Shaffer 2000).
Two beaches within Dungeness Bay are documented surf smelt spawning beaches (Penttila 1999). Comparing ulvoid coverage of these beaches with adjacent non-spawning beaches reveals that spawning beaches have less ulvoid coverage throughout the year (Figure 3).

While fecal coliform levels, an indicator or nutrient loading, have increased significantly in Dungeness Bay between 1989 and 2000 (F=2.28; F crit $_{(11,02,\ 05)}$ =1.809; p=0.0103), ulvoid volume along beaches within Dungeness Bay is not significantly correlated to fecal coliform levels by beach (R^2=0.70; $R^2_{\mathrm{crit}\ 3,01,0.05)}$=0.805) but is significantly correlated to proximity to shoreline alterations (including armoring and stream barriers); R^2=0.94644; $R^2_{\mathrm{crit}\ (4,01,0.05}$=0.729).

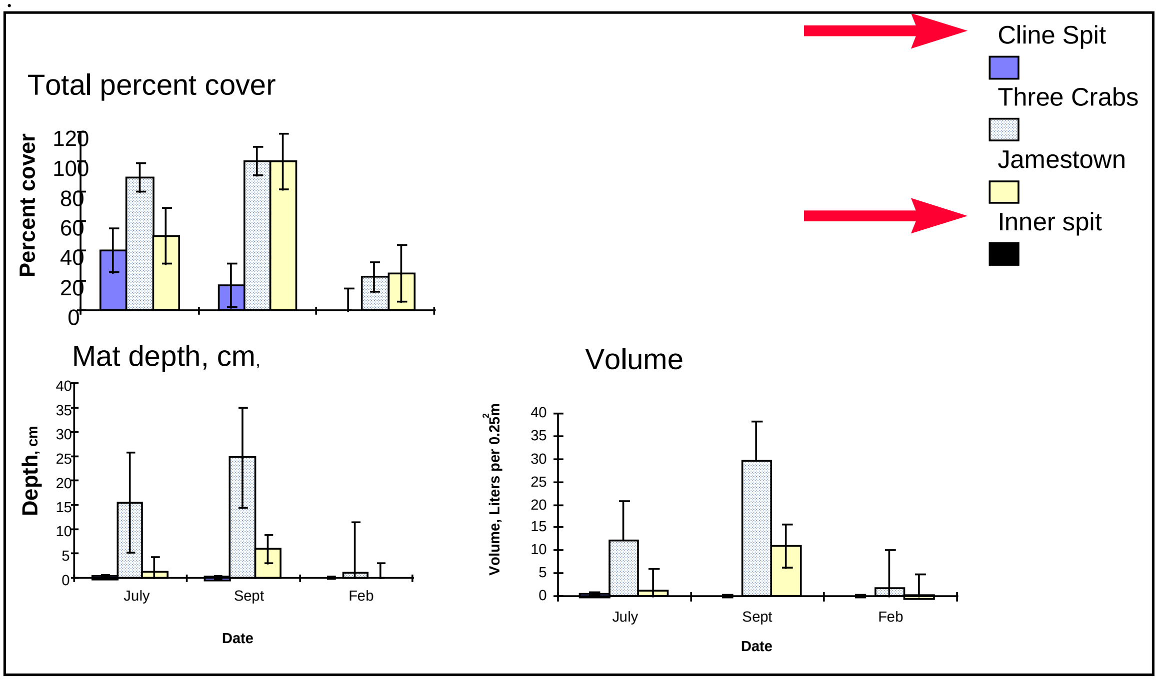

Figure 3 Ulvoid mat coverage within Dungeness Bay (arrows indicate forage fish spawning beaches, all graph units are per quarter meter square).

Discussion

The nearshore environment of the Strait of Juan de Fuca is extremely variable, and defined by local geology, beach elevation, fetch, exposure, and proximity to freshwater sources. Combining work done to date reveals that ulvoid mats within the Strait of Juan de Fuca occur naturally, are variable, and are prominent, and have increased in at least one major embayment (Dungeness Bay). Correlating ulvoid mapping results to physical features of the Strait suggests that: (1) Ulvoid presence is related to nonpoint water sources; (2) Ulvoid presence may be predicted by high fecal coliform levels (an indicator of nutrient levels); (3) Ulvoid mats, when prevalent, appear to alter beach substrate composition and profile; and (4) Ulvoid mats, when prevalent, are correlated to shoreline structures.

The significant relationships observed between ulvoid mats and runoff and fetch are not surprising. To form, these mats require shallow embayments with poor flushing and nutrient sources (Thom and others 1988). Low fetch and proximity to runoff are both features of these types of embayments. Further, nonpoint sources are documented nutrient sources to nearshore areas that may be seasonally nutrient limited (Thom and others 1988). What is unknown is (1) the frequency of nonpoint sources along embayments of inland waters of Washington, including the Strait of Juan de Fuca; (2) the long term trend in nonpoint sources; and (3) the nutrient loads they contribute. These points bear further study.

While fecal coliform do not contribute to ulvoid mats, they are associated with nutrients that do. They may therefore be used as an indicator of water quality change, and in particular, changes in nutrient levels. Dungeness Bay fecal coliform and ulvoid mat coverage are both increasing, but to date are not significantly correlated. Lack of correlation could be due to a small sample size (only 3 beaches had both ulvoid volume and fecal coliform data). Alternatively, it could indicate that a transition is occurring in Dungeness Bay, and ulvoid volumes have yet to respond to increasing loads. It could also indicate additional, or other, factors are contributing to ulvoid mats. Shoreline alterations appear to be a contributing factor. Additional monitoring of water quality (specifically nutrient levels if possible), shoreline features including shoreline alterations, and ulvoid volume would define further the relative contributions of water quality and shoreline alteration to ulvoid blooms in Dungeness Bay.

The relationship between ulvoid mats and beach hydrology is complex and, if the bloom is large enough, results in shifts in physical habitat. Ulvoids interact with the hydrodynamics of a beach in two ways. The first is by slowing water as it flows across the tideflat, thereby causing finer particles to drop out of the water. Such dampening of tidal energy is well documented for other macroalgal systems (Eckman and others 1989; Duggins and others 1990)) and may be reflected in the higher percentage of fine substrate materials at the ulvoid beach compared to the non ulvoid beach documented by Shaffer and Burge (1999). This would also explain the observed beach profile differences. Ulvoid mats were thickest along the shore where substrate was silt and mud. Further offshore the beach experienced greater tidal flushing and wave action, and the substrate shifted to larger particle size. Correlation analysis confirms this trend, and reveals a significant, inverse relationship between ulvoid volume and substrate particle size within an ulvoid beach (Shaffer and Burge 1999).

The second hydrodynamic relationship, between shoreline alterations and ulvoid volume, is also noteworthy. Shoreline alterations, including armoring of shorelines and tidal barriers to streams and rivers, have been documented to significantly alter beach transport processes, including longshore drift (Johannessen 1998; Johnson pers.comm; Pilky and Wright 1988; Shipman 1997). Structures that disrupt longshore drift may also cause ulvoids to accumulate, and subsequent habitat and resource changes to occur. Ulvoid mats therefore may be both a contributor to, and a product of, the disruption of longshore transport.

Ulvoids are therefore an additional risk factor when managing shallow enclosed embayments for shoreline development. They illustrate clearly why water quality (particularly nutrients from nonpoint sources) is an important element of nearshore management. This element has been largely overlooked in nearshore management in the past. For example, tightlines, loosely defined as 6-inch or less diameter pipes, are a common method for transporting nutrient laden stormwater from residential developed sites to the beach. These conveyances are largely unregulated, and are increasingly prevalent along Washington shorelines. The role they play in nearshore water quality is important for future management. It is equally important to recognize that nearshore development, including armoring and alteration of tidal creek flow, effects not only water flow, but also water quality, and may have significant secondary impacts to the physical habitat by promoting accumulation of ulvoid mats.

Interactions between ulvoid mats and biological resources also appear complex. Ulvoid mats may have a positive or negative effect on biological resources. When present within threshold levels ulvoid mats may provide shade and cover for forage fish eggs. When threshold levels exceeded, biological resources may be impacted. Impacts may include creating a substrate barrier that prevents clam recruitment and survival, as well as spawning by adult forage fish, smothering of established shellfish resources, shifts in habitat, including loss of eelgrass beds, and anoxic conditions. Both positive and negative conditions appear to be occurring in Dungeness Bay, as evidenced by Shaffer and Burge 1999, and Shaffer 2000.

For example, Cline Spit, the only beach with both ulvoid mats and surf smelt spawn, had the third highest ulvoid volume of all beaches studied. This beach is in proximity to those beaches with the highest ulvoid mat coverage both on and adjacent to potential spawning habitat, and no spawn. Conversely, many beaches with no ulvoids also had no surf smelt spawn. It is possible that at low levels ulvoid mats may in fact benefit surf smelt spawn by providing shade and retaining water at the spawn sites.

Shade has been documented to be critical for surf smelt spawn survival (Penttila, in press.). This may be the case at the Cline Spit beach, which had high volumes of ulvoids as well as high spawn densities. Alternatively, at higher volumes, ulvoids may prevent spawning by creating a barrier to surf smelt spawning, and may create a hostile anoxic environment for both spawning and egg survival. This may explain why spawn was not found at Three Crabs and Jamestown beaches, which are within two miles of Cline Spit, have similar beach profiles, but much higher ulvoid volumes both on and in proximity to potential spawning habitat. Trends observed in this study support further studies to determine if there is a relationship between ulvoid mat volume and forage fish spawning behavior and egg survival.

The extent of ulvoid mats documented in this study reflects a relationship between ulvoid mats and water quality declines. Dungeness Bay, recently downgraded due to elevated fecal coliform levels in the inner bay (Washington Department of Health 2000), has experienced the highest water quality decline of all embayments within the Strait, and has significantly higher ulvoid volumes than all other beaches sampled. Within Dungeness Bay, areas with high fecal coliform levels also have the highest ulvoid mat volumes (Figure 4).

If a threshold for ulvoid density does exist, declines in water quality, increases in shoreline alterations, and increases in ulvoid mats observed within Dungeness Bay indicate that the spawning area of Cline Spit may be at risk if these trends continue

Results from shellfish work by Shaffer and Burge 1999 indicate that a threshold may have been exceeded for intertidal clams, resulting in lower recruitment and higher mortality of a number of shellfish species within Dungeness Bay.

A number of recommendations on future directions for research and management of ulvoid blooms are evident. For management, water quality needs to be a higher priority in on-the-ground nearshore management. Tightlines, stormwater runoff via small creeks and culverts and other nonpoint sources need to be managed much more actively. Ulvoid blooms should also be considered a type of Harmful Algae Bloom (HAB), and included in respective water quality research and management forums. Shoreline alterations need further consideration for potential for water quality disruption and likelihood ulvoid mat development. Research recommendations of highest priority include:

(1) Defining long term trends in ulvoid mats along additional areas of Washington nearshore.
(2) Defining the relationship between shoreline features and ulvoid mat prevalence.
(3) Defining the relationship between ulvoid mats and forage fish spawning behavior and egg survival.
(4) Quantifying eelgrass bed impacts of ulvoid mats on a Puget Sound scale.
(5) Defining if thresholds between beneficial and hostile ulvoid mat environments exist, and if so, what they are, and areas and resources of highest risk.

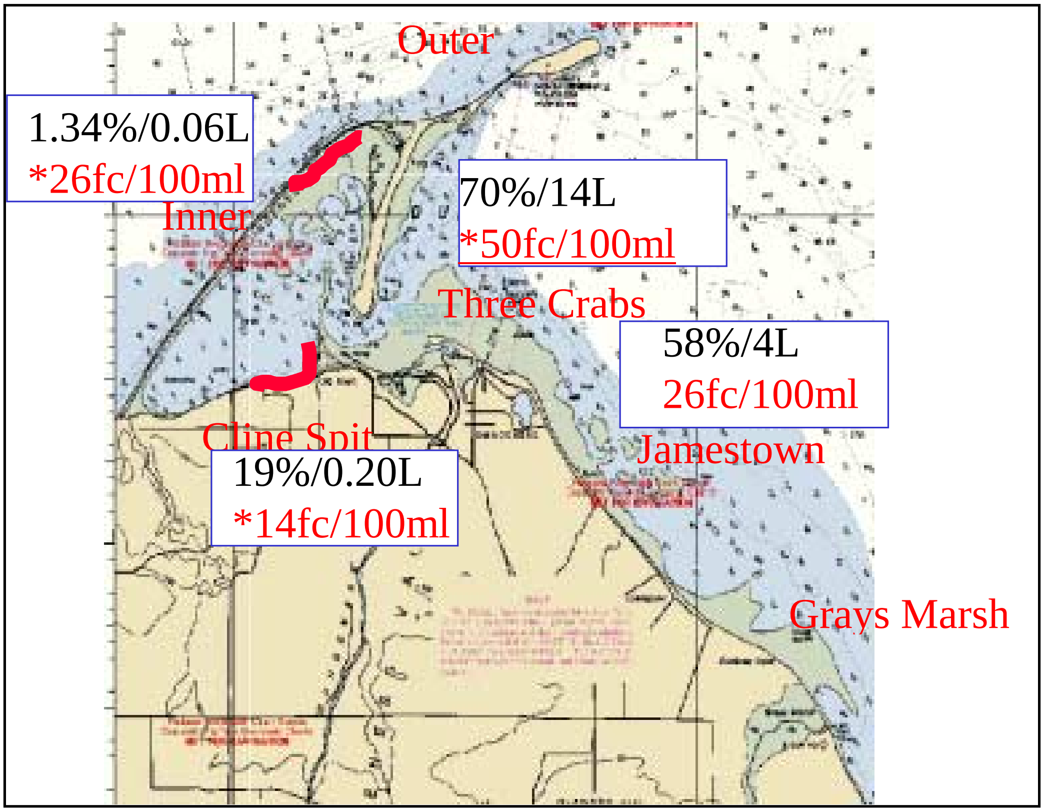

Figure 4 Ulvoid mats (percent cover/volume) and fecal coliform levels, Dungeness Bay. *= Fecal coliform levels increasing; State water quality standards exceeded. Red lines indicate forage fish spawning beds.

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